Naturalness, Dark Matter, and the LHC

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based on arXiv: 1304.7006
with M. Heikinheimo, A. Racioppi, M. Raidal and K. Tuominen

Outline

Goals of this Talk

This is a "workshop" and not a "conference" talk

$\Rightarrow$ I picked a speculative topic that would

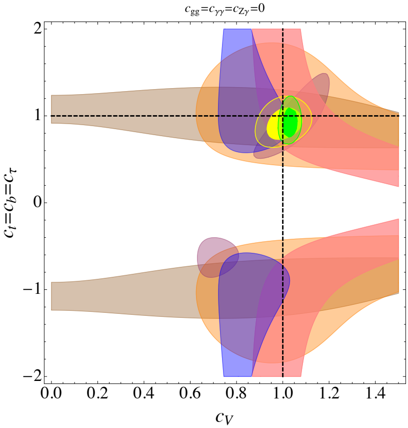
- be interesting (controversial)
- encourage discussion
- help to clarify our understanding

So please feel encouraged to:

- interrupt
- ask questions
- object

After EPS 2013: Standard Model Higgs Boson

Most striking LHC discovery: "a" Higgs boson



- New boson discovered at 125-126 GeV
- Probably spin 0 and positive parity
- Couplings to fermions and bosons consistent with SM

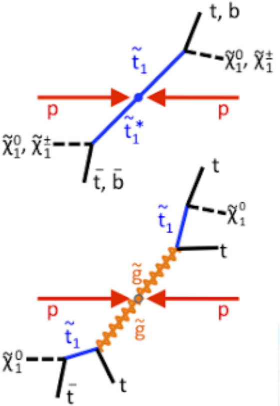
$\Rightarrow$ Elementary scalar?

(plot from Falkowski, Riva, Urbano: 1303.1812)

After EPS 2013: Beyond the Standard Model?

Before the LHC started, new physics was strongly anticipated to appear at the electroweak scale:

- Supersymmetry:
  - stops, squarks
  - sleptons
  - gauginos
  - multiple Higgs bosons
- Compositeness:
  - excited states
- Extra dimensions:
  - KK-modes
- Little Higgs, etc.



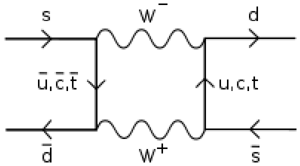
⇒ Those particles should be abundantly produced at the LHC!

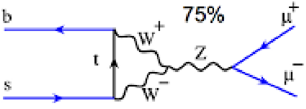
(but none have been found so far)

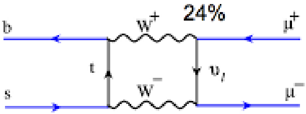
EPS 2013: Flavor and Other Precision Tests

Many observables suppressed by loops, CKM elements and other small parameters:

- Kaon mixing
- Rare decays (like $B_s \to \mu^+\mu^-$)
- other FCNC







Generic new physics?

$\Rightarrow$ Tree level contributions
$\Rightarrow$ Observable for $\Lambda_{NP} \gg \Lambda_{EW}$!

(so far no evidence of anomalous interactions of SM fields)

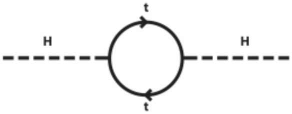
Implications for Modelbuilding?

- "Moderate" fine-tuning, little hierarchy (mini-split SUSY)
  - Nature is fine-tuned, but only at a level of 10^{-3} or 10^{-4}.
  - This happens elsewhere in nature; nothing to worry about.
  - SUSY is probably "just around the corner".
  - We need a bigger machine!
- Non-minimal models (nMSSM and friends)
  - Nature doesn't have to be minimal.
  - Add more degrees of freedom, so more parameters.
  - Can fit experimental absence of new physics while maintaining naturalness.
- Are those the only two possible conclusions?
  - Maybe there is something we have not understood yet...

Quadratic Divergences and Renormalization

First conceptual challenge:

How should we think about quadratic divergences?



$$\Rightarrow \qquad M_H^2 = ?$$

The naive point(s) of view:

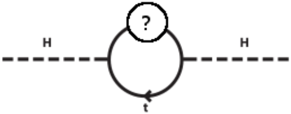
- In cut-off dependent regularization schemes, scalar mass terms get a Λ^2 contribution.
- In dimensional regularization, there is no scale and therefore no such contribution.

Question: Which answer is correct?

Quadratic Divergences and Scale Hierarchy

Answer: The question is not well formulated.

If physics at a mass scale Λ couples to the scalar, dimensional regularization does give quadratic contributions:



$$\Rightarrow \qquad M_H^2 \propto M^2 \log \frac{\Lambda}{M}$$

Scalar masses are naturally as large as the largest mass scale.

⇒ There is a reason why people do not call it the "quadratic divergence problem".

Classical scaling of dimensionful couplings

Second conceptual challenge:

Q: What does RG running of dimensionful couplings mean?

Consider a free field theory (only kinetic and mass terms):

- Let us consider mass terms relative to the renormalization scale ($m = M/R$)
- Decreasing the renormalization scale (R $\downarrow$) increases the relative size of masses ($m \uparrow$)
- It is in this sense that "relevant operators grow at low energies" ($M \gg R$)

A: The actual physical size ($M \approx \Lambda$) of the scalar mass does not change through scaling. Of course, in interacting field theories there are anomalous dimensions, so renormalization scales do matter there.

The SM as an Effective Field Theory

The Wilsonian view of Renormalization:

- Local QFTs have a limited energy range of validity
- Operators are generated by integrating out degrees of freedom of the UV complete theory at a cut-off scale Λ
- Operators can be relevant, marginal or irrelevant

Application to the Standard Model:

- Relevant couplings (Higgs mass parameter) should be of order the cut-off scale $M \approx \Lambda$
- Marginal couplings (Yukawas, gauge couplings, Higgs quartic) should be $\mathcal{O}(1)$ numbers
- Irrelevant operators (such as 4-fermion interactions, S and T parameter) are suppressed by powers of E/Λ

Predictions from Generic UV Physics

If the SM is an effective theory, we expect:

- There can be no elementary scalars below the cutoff-scale
- There should be evidence for dimension 5 and higher operators, if the cutoff-scale is not too high

The problem:
We see a light scalar, but no higher order operators!

The usual solutions to this conflict are:

1. The cutoff-scale is large, but nature is (very) fine-tuned. Then there are (naturally) no effects from higher dimensional operators, since they are scale-suppressed.
2. The cutoff-scale is low, but nature conspires against us so that we see no higher dimensional operators. Light scalars are then perfectly natural. (In SUSY this conspiracy is R-parity and MFW.)

A Third Possibility?

3. There exists no cut-off above the electroweak scale in the Wilsonian sense. No local operators of SM fields are generated at such a scale.

Possible objections:

- But gravity exists! What about the Planck scale?

  $\Rightarrow$ This is the core of the matter. But maybe gravity does not couple in this way to the Standard Model. See e.g.
  - Dubovsky, Gorbenko, Mirbabayi: 1305.6939
  - Farina, Pappadopoulu, Strumia: 1303.7244
  - See also EPS 2013 talk by Giudice
- What about GUTs? How can we explain the SM charges?

  $\Rightarrow$ They are not logically necessary, and also predict proton decay, which has not been observed.

A Third Possibility? – continued

3. There exists no cut-off above the electroweak scale in the Wilsonian sense. No local operators of SM fields are generated at such a scale.

More possible objections:

- What about neutrino masses? The See-saw mechanism predicts a new mass scale!

  $\Rightarrow$ Neutrinos can be Dirac particles, so the see-saw mechanism is not needed.
- What about Dark Matter?

  $\Rightarrow$ The wimp miracle suggests that DM is at or close to the EWSB scale. See the rest of this talk.

What about scale invariance?

Another possible objection:

- If we assume this is true, we loose the Wilsonian understanding of renormalizability of the Standard Model.
- The electroweak scale sets a mass. Why are there no higher order operators from other scales?

If we assume that nature is classically scale invariant, we can understand why:

$\Rightarrow$ The Higgs mass parameter (and therefore the electroweak scale) is generated dynamically, just like Λ_{QCD}.

BUT:
Classical scale invariance does not "solve the hierarchy problem". Scalar masses are always of the order of the highest scale in the theory, no matter if its origin is dynamical or not.

How should nature then look like?

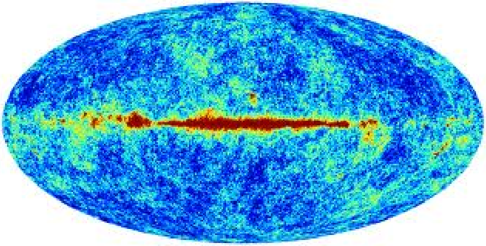
Let us take this seriously for a moment . . .

⇒ What would be predictions of this framework?

- The natural mass scale of all elementary scalars is the electroweak scale.
- If different scalar fields exist, they could be coupled by dimensionless portal couplings like $H^2 S^2$.
- If a VEV is generated for one of those scalars, it would induce mass terms for all others as well.

If we assume that one of the scalars is the Standard Model Higgs, we have a theory for the generation of the EWSB scale and Dark Matter!

Intermission:



Philosophical musings:

- In cosmology, the universe would be completely homogeneous and isotropic without quantum fluctuations.
- All atomic and molecular structures are also generated by quantum effects.
- Speculative Question: Maybe quantum mechanics is also ultimately responsible for mass?

Now back to physics!

Generating the EWSB scale

Examples for mass scales from dimensional transmutation:

1. Confinment of non-Abelian gauge theories (à la QCD)
2. Coleman-Weinberg potential with non-trivial minimum

$\Rightarrow$ Generating the EWSB scale in the visible sector?

1. Techicolor implies dimension 4 operators of SM fields
2. Coleman-Weinberg: Higgs mass one loop factor below gauge boson masses

$\Rightarrow$ No such constraints in the dark sector!

$\Rightarrow$ The mass scale can be generated there and transmitted via portal interactions.

Dark Technicolor Toy Model

Minimal model:

- H: EW doublet scalar
- S: Gauge singlet scalar
- Q_i: Dark fermions
- $F^a_{\mu\nu}$: Dark gluons

Dark sector and portal Lagrangian:

$$\begin{aligned}\mathcal{L} \quad = \quad & |D_\mu H|^2 - \lambda_h (H^\dagger H)^2 + |\partial_\mu S|^2 - \lambda_s |S|^4 \\ & -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + \sum_{i=1}^{N_f} \bar{Q}_i (i\gamma^\mu D_\mu) Q_i \\ & + g_h |S|^2 |H|^2 - (y_Q S \bar{Q} Q + \mathrm{h.c.})\end{aligned}$$

Dark Sector Chiral Symmetry Breaking

Depending on the gauge group and fermion representation, the dark sector chiral symmetry breaking pattern can be:

$$\begin{array}{ll} \mathrm{SU}(N_f) \times \mathrm{SU}(N_f) \to \mathrm{SU}(N_f) & \text{(complex)} \\ \mathrm{SU}(2N_f) \to \mathrm{Sp}(2N_f) & \text{(pseudoreal)} \\ \mathrm{SU}(2N_f) \to \mathrm{SO}(2N_f) & \text{(real)} \end{array}$$

If the fermions are in a complex representation, the low energy theory contains:

- heavy, stable dark baryons with $M_B \approx \Lambda_{DTC}$
- (up to this point) massless mesons as NGBs of the broken chiral symmetry

(as familiar from QCD)

Stabilizing Dark Matter

The composite dark matter can be stabilized in two ways:

1. The dark baryons carry a conserved $U(1)$ charge (dark baryon number)
2. For $N_f \neq 1$: Additional flavor symmetries protecting dark mesons

For real or pseudoreal representations:
$\Rightarrow$ Some mesons can also carry dark baryon-number

Mesons are in general better thermal dark matter, because $M_{DM} \neq \Lambda_{DTC}$

$\Rightarrow$ More freedom to get the correct relic density

Low Energy Dynamics in the Dark Sector

QCD-like chiral perturbation theory of low energy dynamics, using a linear representation:

$$V = -\frac{m^2}{2}\mathrm{Tr}(M^\dagger M) + \lambda_1 \mathrm{Tr}(M^\dagger M)^2 + \frac{\lambda_2}{4}(\mathrm{Tr}(M^\dagger M))^2,$$

M is the dark meson matrix

$$M = \frac{1}{2}\left(\sigma + i\eta + 2\sqrt{2}(\sigma^a + i\pi^a)X^a\right) E$$

where

- σ is the scalar field component that gets a VEV
- π^a are the pseudoscalar NBGs
- σ^a are massive scalar mesons

Generating VEVs for the Scalar Fields

Messenger scalar-dark techniquark Yukawa coupling:
$\Rightarrow$ coupling between messenger S and the $\bar{Q}Q$ condensate

$$\langle \bar{Q}Q \rangle \sim \Lambda_{\rm TC}^3 S$$

Minimizing the effective potential

$$V_s = \lambda_h h^4 + \lambda_\sigma(\sigma^2 - v_\sigma^2)^2 - g_h s^2 h^2 + g_\sigma s^2 \sigma^2 + \lambda_s s^4 + v_\sigma^3 s$$

yields

$$\langle \sigma \rangle = v_\sigma \sim \Lambda_{\rm TC} \qquad \langle s \rangle = \alpha v_\sigma \qquad \langle h \rangle = \frac{\sqrt{g_h}}{\sqrt{2\lambda_h}} \langle s \rangle$$

Scalar Mass Hierachy

The suppression factor $\alpha \approx g_\sigma$ is:

$$\alpha = \frac{2\sqrt[3]{3}g_\sigma\lambda_s + \left(9\lambda_s^2 - \lambda_s\sqrt{3\lambda_s(8g_\sigma^3 + 27\lambda_s)}\right)^{\frac{2}{3}}}{2\sqrt[3]{9}\lambda_s\left(9\lambda_s^2 - \lambda_s\sqrt{3\lambda_s(8g_\sigma^3 + 27\lambda_s)}\right)^{\frac{1}{3}}}.$$

Masses of the scalar states:

$$\begin{aligned} m_\sigma^2 &= (8\lambda_\sigma + 2g_\sigma\alpha)v_\sigma^2 + \mathcal{O}(g_h), \\ m_s^2 &= 4g_\sigma\alpha v_\sigma^2 + \mathcal{O}(g_h), \\ m_h^2 &= 4g_h\alpha^2 v_\sigma^2 + \mathcal{O}(g_h^2). \end{aligned}$$

Mixing angles between the scalar states:

$$\tan(\sigma, s) \approx \mathcal{O}(g_\sigma^2) \qquad \tan(h, s) \approx \mathcal{O}(g_h^{3/2} g_\sigma)$$

Dark Matter Candidates

We asume:

- Dark matter is a technipion π_0 with $U(1)_{TB}$ charge
- The main annihilation channel is $\pi_0\bar{\pi}_0 \to hh$
- Scalar mixing implies also $\pi_0\bar{\pi}_0 \to \mathrm{SM}$

Taking this into account we estimate the thermally averaged cross section as

$$\langle v\sigma\rangle \sim \frac{g_h^2\alpha^2}{8192\pi}\frac{\hat{m}_s^4\sqrt{1-\hat{m}_h^2}}{(1-\frac{1}{4}\hat{m}_s^2)^2}\frac{1}{m_\pi^2},$$

where $\hat{m}_i \equiv m_i/m_\pi$.

Conclusions from Dark Matter Model

The natural ordering of masses in the scalar sector:

$$m_\sigma^2 \gg m_s^2 \gg m_h^2.$$

The dark matter mass is also suppressed relative to the composite scalar:

$$m_\sigma^2 \gg m_\pi^2$$

$\Rightarrow$ Two phenomenologically interesting regions:

1. $m_s \gg m_\pi > m_h$:
   Implies light dark matter, e.g. $m_\pi \sim \mathcal{O}(100\text{ GeV})$ and $g_h\alpha \sim \mathcal{O}(0.1)$.
2. $m_s \sim m_\pi > m_h$
   Implies measurable deviations from SM in Higgs couplings due to mixing with s.

Summary

1. The hierarchy problem is properly named. It is not the "quadratic divergence problem".
2. The existence of a light Higgs and the absence of any new physics might indicate that there is no UV cutoff-scale in the Wilsonian sense
3. This implies that all elementary scalars have to live at or close to the electroweak scale.
4. Any such scalars can couple to each other through portals.
5. EWSB could be explained to originate from Dark Matter in such a framework.